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Effect of Cut Quality on Hybrid Laser Arc Welding of Thick Section Steels

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Abstract

From an industrial point of view, in a laser cutting-welding production chain, it is of great importance to know the influence of the attainable laser cut quality on the subsequent hybrid laser arc welding process. Many studies have been carried out in the literature to obtain lower surface roughness values on the laser cut edge. However, in practice, the cost and reliability of the cutting process is crucial and it does not always comply with obtaining the highest surface quality. In this study, a number of experiments on 25 mm steel plates were carried out to evaluate the influence of cut surface quality on the final quality of the subsequent hybrid laser welded joints. The different cut surfaces were obtained by different industrial cutting methods including laser cutting, abrasive water cutting, plasma cutting, and milling. It was found that the mentioned cutting methods could be used as preparation processes for the subsequent hybrid laser arc welding. However, cut quality could determine the choice of process parameters of the following hybrid laser arc welding.

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Keywords: Laser cutting; Hybrid Laser Arc Welding; Cut quality; Weld quality

1. Introduction

Manufacturing of large steel constructions demands the ability of processing thick section steels. By taking the advantages of high power laser cutting and hybrid laser arc welding (HLAW) it is possible to process thick section

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steels with thickness of above 25 mm. Recent studies on laser welding (Farrokhi et al., 2015) and cutting (Goppold et al., 2014) of steels with lower thicknesses show that the unique characteristics of solid-state lasers can result in high quality products. However, some crucial challenges appear when it comes to processing of thick section steels. For instance, in addition to the well-anticipated defects, such as, concavity, undercut, and root humping, HLAW has been found to have higher tendency to form porosity in the root side with increasing plate thickness (Dilthey et al., 2005). It is difficult to avoid solidification cracks when welding 40 mm thick double-sided steel joints (Nielsen, 2014). In the case of laser cutting the striations and dross attachments, which are left on the sides and bottom of the kerf respectively, are known as the main quality challenges of thick section laser cutting (Wandera et al., 2011).

A great deal of research has been conducted to find technical means to overcome the mentioned challenges and to obtain lower cut surface roughness values (Goppold et al., 2014); (Wandera et al., 2011). Striation-free cuts of thin steel sheets by using fiber lasers with modified process parameters have been reported in some studies (Powell et al., 2011); (Sobih et al., 2007). However, from an industrial point of view, in a laser cutting-welding production chain, it is of great importance to know the influence of the attainable laser cut edge quality on the subsequent HLAW operation. In practice, the cost and reliability of the cutting process is crucial and it does not always comply with obtaining a fully perpendicular cut with a low surface roughness on the edge. Recent studies about reduced pressure laser welding of 40 mm thick low alloyed steel shows that the combination of increased edge surface roughness and a pre-set air gap increases the weld penetration in the butt joint configuration (Sokolov et al., 2015). In addition, the significance of the edge surface roughness on the laser absorption at power levels of above 10 kW has been reported by another study (Sokolov et al., 2012). Therefore, one can argue that influence of cut quality and surface roughness must be taken into consideration when laser welding thick section steel, as the processing of higher thicknesses requires the laser power levels above 10 kW. However, despite the importance of the subject, only a few studies are available about the influence of cut surface quality on the following HLAW of thick section steels.

The aim of this study is to investigate the effect of different cut surface qualities of 25 mm thick section steels on the final quality of the subsequent hybrid laser arc welded joints and the welding procedure. A number of experiments were carried out to obtain the different cut surface qualities by milling and the common industrial cutting methods including laser cutting (LC), plasma cutting (PC), and abrasive water cutting (WC). The cut samples were prepared for butt joint configuration and welded by a high power solid-state laser. The final quality of the welded joints was compared between laser cut samples and samples cut with alternative industrial choices. Figure 1 shows the structure of study.

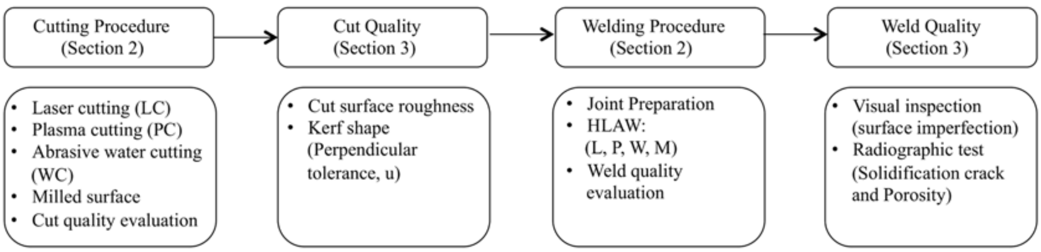

Fig. 1. Structure of study.

2. Experimental Procedure

2.1. Cutting Procedure

The laser used for the cutting was an IPG Photonics YLS- 3000SM fiber laser providing a 3 kW single mode, continuous wave laser beam with a wavelength of 1076 nm. The laser was guided through an optical fiber to a High Yag cutting head (focal length: 470mm) and cutting was performed with Nitrogen as the assist gas. S355 Mild steel plates with a thickness of 25 mm and 120 mm x 100 mm dimensions were considered for this study. The chemical composition of the steel can be found in table 1. The samples were cut into two 50 mm x 120 mm pieces by laser cutting (4 samples), abrasive water cutting (6 samples), and plasma cutting (one sample) and then prepared for butt joint configuration. In addition, two samples were milled at the cut edge to be considered as a high quality reference. Unfortunately, due to practical limitations the number of samples for different cutting methods was not equal.

Table 1. Chemical composition of the steel (%) (after the material certificate provided by the steel manufacture).

	C	Mn	P	S	Si	Cu	Al	Ni	Cr	V	Nb	Mo	Ti	N	CEV
S355J2	0.14	1.45	0.015	0.003	0.20	0.02	0.033	0.01	0.04	0.004	0.028	0.002	0.002	0.004	0.39

The process parameters of cutting have been provided separately for each cutting method in tables 2 to 4. For the plasma cutting and abrasive water cutting, standard industrial cutting parameters were chosen which typically have the highest achievable quality. For the laser cutting, the process parameters were slightly changed to obtain different cut qualities at the edges. It should be noted that the plasma cut samples were sand blasted to remove the oxide layer from the cut surface.

Table 2. Abrasive water cutting process parameters. The numbers after WC (1 to 3) indicate the experiments number that is followed by a letter (a or b) referring to the different qualities.

	Travel speed (mm/min)	Abrasive type	Abrasive mass flow rate (g/min)	Nozzle standoff (mm)	Nozzle diameter (mm)	Water pressure (bar)
WC1-3 a	20.8	GMA Garnet	400	2	0.7	3500
WC1-3 b	34.4	GMA Garnet	400	2	0.7	3500

Table 3. Plasma cutting process parameters.

	Travel speed (mm/min)	Gas type	Gas pressure (bar)	Nozzle standoff (mm)	Voltage (V)	Current (A)
PC	1000	O_2	10	5	148	200

Table 4. Laser cutting process parameters. The letter after LC indicates the different qualities (a to d).

	Travel speed (mm/min)	Gas type	Gas pressure (bar)	Nozzle standoff (mm)	Nozzle diameter (mm)	Laser power (kW)	Focal point position (mm) *
LC a	60	N_2	10	1	2.5	3	+12
LC b	60	N_2	5	1	2.5	3	-12
LC c	60	N_2	10	1	2.5	3	-25
LC d	60	N_2	15	1	2.5	3	-12

* - below work piece surface, + above work piece surface.

After the cutting, the surface roughness (Ra) and the perpendicular tolerance (u) of the edges were measured as the two major quality factors for the cut samples (see figure 2). The surface roughness was measured in three areas: upper, middle, and lower zones and was calculated as the arithmetic average of the surface deviations values. Each set of measurement was repeated in the center of the cut surface as well as on the sides with a 20 mm distance from the start and stop points. In order to evaluate the cut kerf shape one narrow slice was cut out from each sample to measure the distance of the cut surface at 20 points with respect to a perpendicular backstop. The perpendicular tolerance of cut edges was calculated by subtracting the minimum distance from the maximum distance. It should be noted that the measurements within a distance of 1.5 mm from the top and bottom sides were excluded from the evaluation.

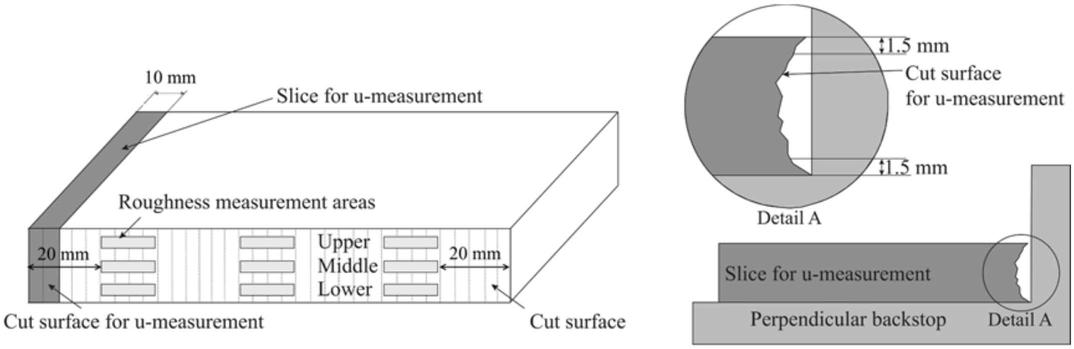

Fig.2. Measurement of surface roughness and perpendicularity of the cut surface.

2.2. Welding Procedure

The laser for HLAW was a Trumpf TruDisk 16002 disk laser providing a 16 kW, continuous wave laser beam with a wavelength of 1030 nm. The laser was guided through an optical fiber to a TRUMPF RFO 600 Reflecting Focus Optics (focal length: 600 mm). The HLAW was provided by the combination of the laser and a MAG system with a gas containing 92Ar $8CO_2$. The filler material was Esab OK 12.50 filler wire with a diameter of 1.2 mm. The welding process parameters, except the laser power and wire speed, were kept constant (see table 5). Cold metal transfer method (CMT) was used as arc transfer mode. Double sided welding was performed by an arc-leading process, in which the arc was exposed 1 second before the laser hit the weld pool. For the joints that had abrasive water cut surfaces (Wa1-3 and Wb1-3) or had milled surfaces (M1 and M2), welding process variables were the same at both sides. However, different process variables were used when welding the joints with plasma cut surfaces (P) and the joints with laser cut surfaces (L1 and L2). The cut edges were placed against each other with as cut condition to form a butt joint configuration for the welding. Since the air gap tends to open during welding, the plates must be pressed together firmly. Therefore, the plates were tack welded in both the start and the stop sides. Air gap was kept between 0 to 0.2 mm for all the joints. After the welding, the start and stop sections of the welds with a length of 25 mm were discarded in order to ensure the quality evaluation was performed based on the steady state section. Therefore, only the remaining 70 mm weld in the middle section was considered for the following visual inspection and radiographic test. The height of the weld beads was measured by a caliper and then the samples were examined by radiographic test to detect possible porosity and cracks in the welds.

Table 5. HLAW process parameters.

Laser power (kW)	Wire feed (m/min)	Travel speed (m/min)	Gas flow rate (l/min)	Focal point position (mm)	Focal length (mm)	Nozzle standoff (mm)	Nozzle diameter (mm)	Arc voltage (V)	Arc current (A)
8, 12, 14	5, 8	0.5	25	-10	600	20	20	21.1	144

3. Results and Discussion

3.1. Cut Quality

The results of surface roughness measurements for different cutting methods can be seen in figure 3. Each column represents the average roughness value of the corresponding area. According to the figure 3, in terms of surface roughness quality, the milled surface and the laser cut surface have the highest and the lowest quality respectively. Plasma cutting and abrasive water cutting also resulted in relatively smooth surfaces with low roughness values. Except for the milled samples that had an almost uniform quality throughout the entire cut surface, in almost all the other kinds of cuts, surface roughness was at its maximum at the bottom side. However, this was more profound in the case of laser cuts. The high roughness values at the laser cut surfaces are related to the deep striations that appear during the cutting process. Especially, in the lower side of the cut surface where the molten material is ejected from the cut kerf, the depth of the striations were significantly deep leading to high roughness values of up to 32 μm.

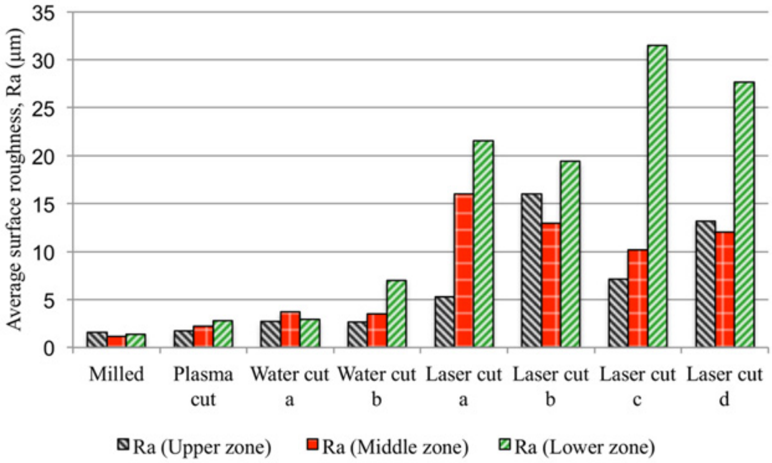

Fig. 2. Results of surface roughness measurement.

Another factor that can determine the cut quality is the kerf shape. Figure 4 shows the kerf profiles based on the microscopic measurements of edge perpendicularity for both left side (u_L) and right side (u_R). It should be noted that due to the variation of the kerf shape along the cut length (especially in the case of laser cuts), the measurements were done as an average of the cut perpendicularity within the entire width of the slides. According to the figure 4 and the mean values of u (u_M) plasma cuts have the lowest perpendicularity, creating a wide gap at the topside. Surprisingly, one side of the cut kerf tended to lose perpendicularity linearly by an angle of about 5 degrees while the other side was more or less perpendicular. This profile almost made a V-shape joint for the subsequent butt joint welding. Laser cutting and abrasive water cutting provided kerf shapes with only a small deviation in perpendicularity. Abrasive water cutting resulted in stable and uniform edges throughout the cut length with a maximum deviation of 0.3 mm at the upper side. In the case of laser cut edges, one reason for the perpendicularity deviation is the presence of the deep striations that are distributed along the cut length with a chaotic manner. Another reason can be the shape of the laser beam inside the cut kerf. When the beam is focused at the half-thickness of the plate the cut kerf tends to open at the bottom. However, the maximum deviation in perpendicularity of the laser cuts was not more than 0.2 mm. Finally, as was expected, the milled edges had a very low u value that guarantees a zero gap for butt joint configuration, if needed.

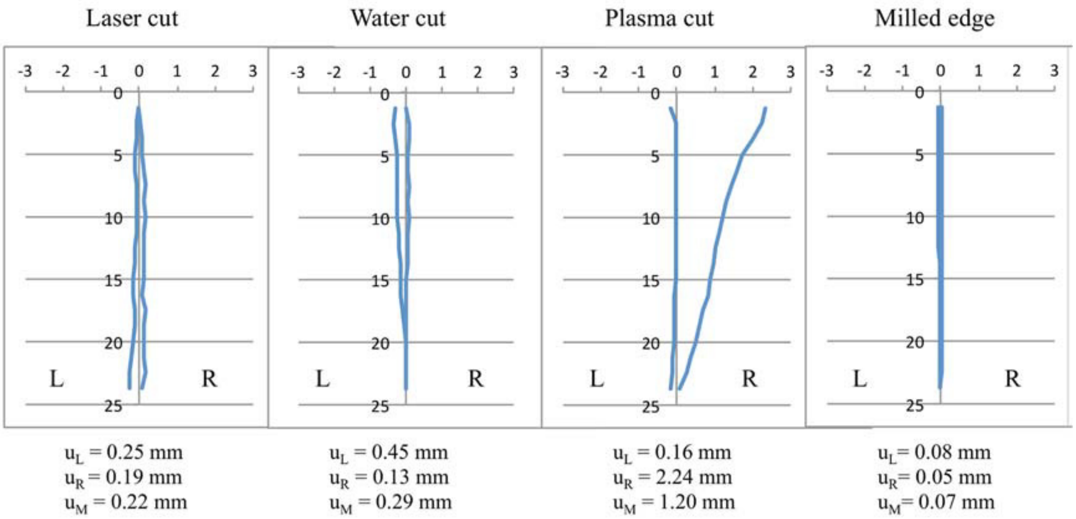

Fig. 3. Kerf shapes and the corresponding perpendicular tolerances for mean value (U_M), left side (U_L), and right side (U_R). Laser cut: LC d. Abrasive water cut: WC1 a.

3.2. Weld Quality

HLAW was carried out for each specimen according to table 6 process variables. Based on the characteristics of different samples that had been prepared with different cutting methods, laser power and wire feed rate varied to obtain complete welds. In the case of plasma cut joint (P), first the bottom (side 1) was welded and then the groove was filled up from the other side (side 2) due to the low perpendicularity and the V-shape groove. Welding was done with an extra filler wire feed in order to provide enough filler material into the wide groove.

Table 6. HLAW process variables and the results of penetration.

	Wa1-3 (both sides)	Wb1-3 (both sides)	M1-2 (both sides)	La (both sides)	Lb (both sides)	Lc-d (side 1)	Lc-d (side 2)	P (side 1)	P (side 2)
Laser power (kW)	14	14	14	14	12	8	14	8	8
Wire feed (m/min)	5	5	5	5	8	5	5	5	8
Results	Full penetration	Full penetration	Full penetration	Drop through	Drop through	Full penetration		Full penetration	

The numbers after W (1 to 3) and M (1 to 2) refer to the experiments number. In general, the uniformity and high quality of abrasive water cut surfaces and milled surfaces, which are appropriate for butt joint configuration, enabled a higher stability of the welding process. All the water cut joints (Wa and Wb) and milled surface joints (M1-2) were welded with 14 kW laser power and 5 m/min wire feed rate from both sides. However, the joints that had laser cut surfaces (La to Ld) required less laser power for welding. As can be seen in figure 5 the mentioned welding parameters led to a complete weld with the water cut joint Wb3, but when the same parameters applied for the laser cut joint (La) it resulted the weld pool to drop through the joint. Interestingly, even a reduction of 2 kW in laser power (Lb) did not help to avoid the excessive penetration of laser through the joint. However, when the laser power was reduced to 8 kW at side 1, it was possible to weld the plates successfully. This can be explained by two possible mechanisms that lead to the less laser power requirement when welding laser cut joints compared with welding the joints with higher surface quality:

- Increased absorption of the laser beam due to the high roughness in the laser cut surfaces leads to excessive heat and higher melting rate at the weld pool. The excessive heat at the joint together with the unavoidable local air gaps that are formed by the non-uniform striations on the cut surface, blow the low viscous molten material away from the bottom.
- Locally increased air gap due to the local instabilities of the striations is high enough to let the high power laser beam pass through the joint and turn the welding process into a cutting process.

However, further studies with the higher number of replicates are required to obtain a more precise explanation for this phenomenon.

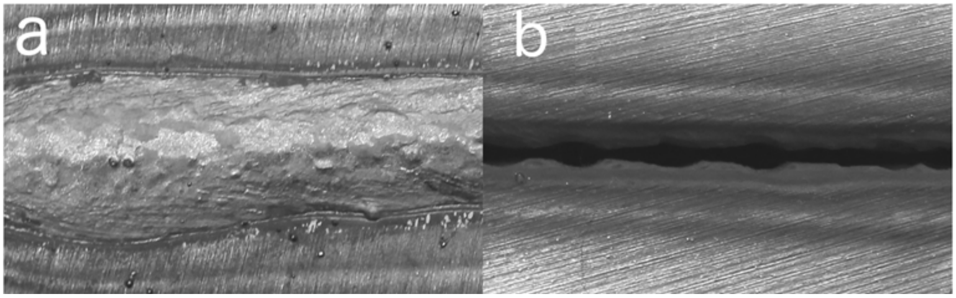

Fig. 5. (a) Abrasive water cut joint Wb3 welded with 14 kW laser power, 0.5 m/min travel speed, 5 m/min wire feed, zero gap assembly, (b) Laser cut joint La, welded with the same parameters but resulted in drop through.

According to EN ISO 12932 all the welds were acceptable visually in terms of surface imperfections. The height of the weld bead barely reached 2 mm with respect to the plate surface, which is acceptable according to the standard. However, the main challenge of HLAW of thick section steels is to avoid cracks and porosity in the weld. Table 7 summarizes the results of radiographic examination for all the welds. Cracks appeared in 5 welds out of 11 experiments.

Table 7. Internal defects (X-ray examination).

	Wa1	Wa2	Wa3	Wb1	Wb2	Wb3	M1	M2	Lc	Ld	P
Crack	1	1	1	No	No	No	No	No	1	No	1
Porosity	No	No	No	No	No	No	No	No	No	No	10 mm*

* The last 10 mm of the weld.

All the cracks appeared in the middle zone where the cooling rate could be higher due to the laser-dominating zone of the welding. In addition, as the cracks were detected almost on the centerline and were perpendicular to the solidification direction, they were identified as solidification cracks. Moreover, the working environment and the filler material had been kept hydrogen free and this type of steel doesn't include martensitic microstructures in the weld zone. Therefore, it is less likely that cold cracks appear compared to solidification cracks. However, all the cracks were non-continuous and limited to 1 to 3 mm in both length and depth. The largest crack was detected in the weld Lc that is shown in figure 6. No correlation was found between cut quality and the occurrence of solidification cracks in the welds. Aside from a few small pores, no porosity was detected in the welds except for the plasma cut joint P that had porosity in the last 10 mm of the evaluated section.

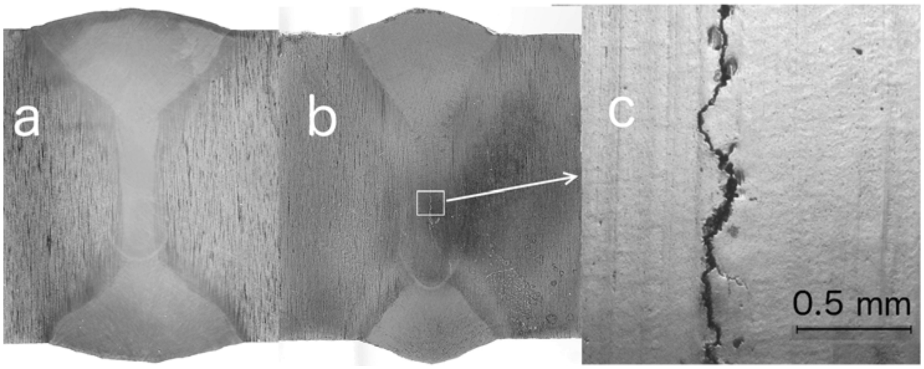

Fig. 4. (a) An example of a flawless weld M1, and (b) the weld with the largest solidification crack Lc. (c) Partial microscopic view of the crack.

4. Conclusion

In this study, a number of experiments on 25 mm steel plates were carried out to evaluate the influence of cut surface quality on the final quality of the subsequent hybrid laser welded joints. The final quality of the welded joints was compared between the joints whose cut surfaces were obtained by laser cutting and alternative choices of cutting methods namely plasma cutting, abrasive water cutting, and milling. Based on the results of experiments following conclusions can be drawn:

- Aside from the milled surfaces, which had the highest quality in terms of both perpendicularity (0.07 mm deviation) and surface roughness (1.4 μm average surface roughness), the product of abrasive water cutting had an appropriate balance of surface quality. Laser cutting and plasma cutting resulted in the worst quality in terms of surface roughness and perpendicularity respectively.

- Based on the results of welding it was concluded that milled samples as well as cut plates obtained by abrasive cutting, plasma cutting, and laser cutting could be used for the subsequent hybrid laser arc welding process.

- No correlation was found between cut quality and weld quality in terms of the number of solidification cracks in the welds. However, it was found that cut quality could determine the choice of process parameter values of the subsequent hybrid laser arc welding.

- The low perpendicularity of plasma cuts resulted in V-shape grooves at the butt joints. Therefore, a 60% increasing of the filler material was required to fill the gap during welding.

- The uniformity and high quality of abrasive water cut surfaces, which are appropriate for butt joint configuration, enabled a higher stability for the welding process.

- Laser cut surfaces required about 20% less laser power for welding compared to water jet cut and milled samples with the same joint assembly (tight gap). This can be because of the fact that the striations of the laser cut surfaces could either (i) increase the laser absorption and brought excessive heat to the joint or (ii) it locally increased the air gap at the joints and let the laser beam cut through. However, more systematic studies with the higher number of replicates are required to obtain a more precise explanation for this phenomenon. Further studies are to be conducted to investigate the effect of laser cut quality on the efficiency of the following hybrid laser arc welding.

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